AUTOCOMPENSATIVE SYSTEM FOR MEASUREMENT OF THE CAPACITANCES

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Abstract

A simple and successful design of an autocompensative system with flip-flop sensor for measurement of capacitances is presented. The analysis of the sensor is based on the state description with the vertical rise segments of the control pulse. The theoretical results are compared with measured data and good agreement is reported.

Keywords

Flip-flop sensor, equivalent voltage, measurement, capacitance.

1. Introduction

The main part of the autocompensative system is flip-flop sensor [1], [3], [5]. The flip-flop sensor is part of a class of silicon sensors with a digital output. Standard flip-flop consisting of two transistors and two resistors (Fig.1) is characterized with two stable states. One of the authors of the patent flip-flop sensor was Lian [1] who showed that flip-flop sensor can be used for measurement of non-electrical quantity and derived formula for calculation of equivalent voltage of the flip-flop sensor controlled by slow-rise control pulse. The principle of measurement is based on this that measured non-electrical quantity will break the value symmetry of the inverters relative to the morphological symmetry axis passing through points *K* and *Z*. However it can be compensated by a voltage $U_N = U_{NE}$ in such way that by repeated connection to a source I(t) the 50% state [1] is restored, so that the magnitude of the measured non-electrical quantity will be reflected into the voltage U_{NE}, which we will call the equivalent voltage. If needed, however, it is not necessary to stick to the custom of using sensometric elements in Fig. 1.

The formula for calculation of equivalent voltage of flip-flop sensor controlled by vertical rise segments of the control pulse [3] was first derived by Kollar [2]. The autocompensative system, in which the equivalent voltage is set automatically depending on the asymmetry, was first published in [4].

The goal of this paper is to show the possibility of measurement of capacitances with autocompensative system with flip-flop sensor and derivation of formula for equivalent voltage.

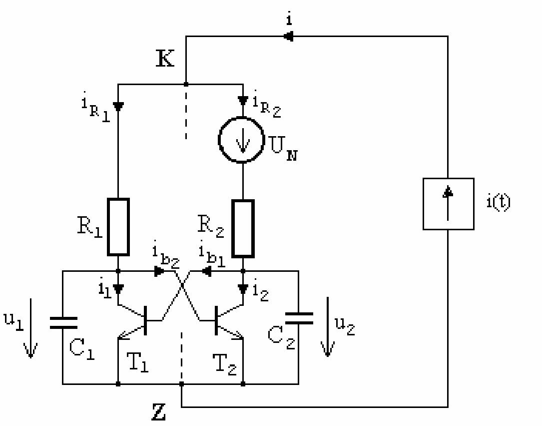

Fig. 1 Flip-Flop sensor. Capacitances C_1 and C_2 represent parasitic capacitances of the transistors T_1, T_2.

2. State description

The flip-flop sensor can be described by system of differential equations [3]

$$\frac{du_1}{dt} = -\frac{\left(u_1 - u_2 - U_N - R_2 i(t) + (R_1 + R_2)\phi_1\right)}{(R_1 + R_2)C_1} \equiv Q_1 \tag{1}$$

$$\frac{du_2}{dt} = -\frac{\left(u_2 - u_1 + U_N - R_1 i(t) + (R_1 + R_2)\phi_2\right)}{(R_1 + R_2)C_2} \equiv Q_2 \tag{2}$$

where ϕ_1, ϕ_2 are defined as

$$\phi_1 = i_1 + i_2/\beta_2, \quad \phi_2 = i_2 + i_1/\beta_1 \tag{3}$$

and

$$i_1 = i_{ES1}\exp(u_2/V_T), \quad i_2 = i_{ES2}\exp(u_1/V_T) \tag{4}$$

where β_1, β_2 are current gains, i_{ES1}, i_{ES2} are saturation currents of bipolar transistors and V_T is thermal voltage.

3. Formula for the equivalent voltage

In the case of control with the vertical rise segments of the control pulse the currents passing through capacitors (C_1, C_2) are not negligible compared to the transistors currents of the flip-flop sensors. It is obvious that unequal values of capacitances C_1, C_2 will break the value symmetry of the inverters of the flip-flop sensor but can be compensated by voltage $U_N = U_{NE}$, what was described above.

In the case of value symmetry it is not possible to decide about the logical level of the output voltage of the inverter R_1, T_1 or R_2, T_2, after connection to a current source. The reason is that the occurrence of a logical one at the mentioned output of the inverter has a statistical character. With a sufficiently large number of connections N to the current source the probability $P(N_1/N)$ of the occurrence of logical ones N_1 at the inverter output is 0.5 (50% state).

In the case of value asymmetry this similarity is broken, but if $U_N = U_{NE}$, then the 50% state is restored and again it is not possible to decide about the logical level of the output voltage of the inverter R_1, T_1 or R_2, T_2.

System of the differential equations (1), (2) was solved in [2]. In the case of value symmetry solution of the system (1), (2) without effect of a noise, has the form [2]

$$u_1 = u_2 \tag{5}$$

Let current amplifications coefficients, the saturation currents of the bipolar transistors and resistors of the flip-flop sensor are equal and let the solution of the system (1), (2), in the case that $C_1 \neq C_2$, is function (5), then for equivalent voltage we have:

$$u_{NE}(u) = R\frac{\Delta C}{2C} I_m - \frac{2R\Delta C}{C}\phi(u,u) \tag{6}$$

where I_m is amplitude of current control pulse, $C_1 = C + \Delta C$ $R = R_1 = R_2$, $\phi = \phi_1 = \phi_2$, $u = u_1 = u_2$ and $C_2 = C$. Eqn. (6) was derived through (1), (2) under condition $\Delta C/ C << 1$. Equivalent voltage as a function of the voltage u, calculated by (6), secures a transition into unstable state S (Fig. 2), without effect of a noise. The function (5) represents a separatrix [3]. The separatrix T_1 (Fig. 2) has a key role in the functioning of the sensor. The separatrix divides the state plane into two regions containing the attractors 1 and 0. If the origin is located on the same side of the separatrix as the point 1, it means that during each control pulse the flip-flop will go into state 1. A change of the equilibrium 1 into 0 can be achieved by using the voltage U_N in such way that the origin lies on the same side of the separatrix T_1 as the point 0. This principle was theoretically described in [3] and mathematically was solved in [2]. Hence the decision about a transition into state 1 or 0 is made in the origin of the state plane as was described above. But there currents ϕ_1, ϕ_2 are negligible compared to the capacitance currents and then factor 2 containing $\phi(u,u)$ in (6) can be neglected. Final formula for the equivalent voltage is then

$$U_{NE} = \frac{R\Delta C}{2C} I_m \tag{7}$$

This idea to assume a solution of the system (1), (2) in the case of the value asymmetry when $U_N = U_{NE}$, as function $u_1 = u_2$ was first used in [2].

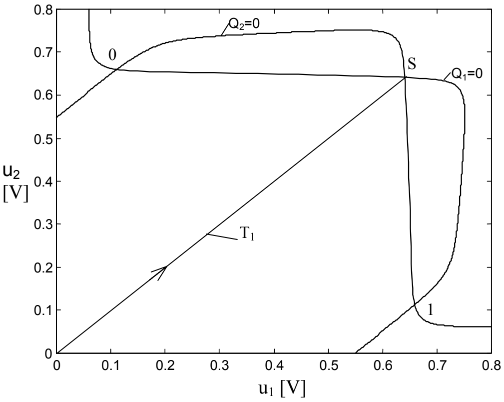

Fig. 2 State trajectory T_1 represents a transition to state S.

In Fig. 2, $Q_1 = 0$, $Q_2 = 0$ represent characteristics of first and second inverter of the flip-flip sensor.

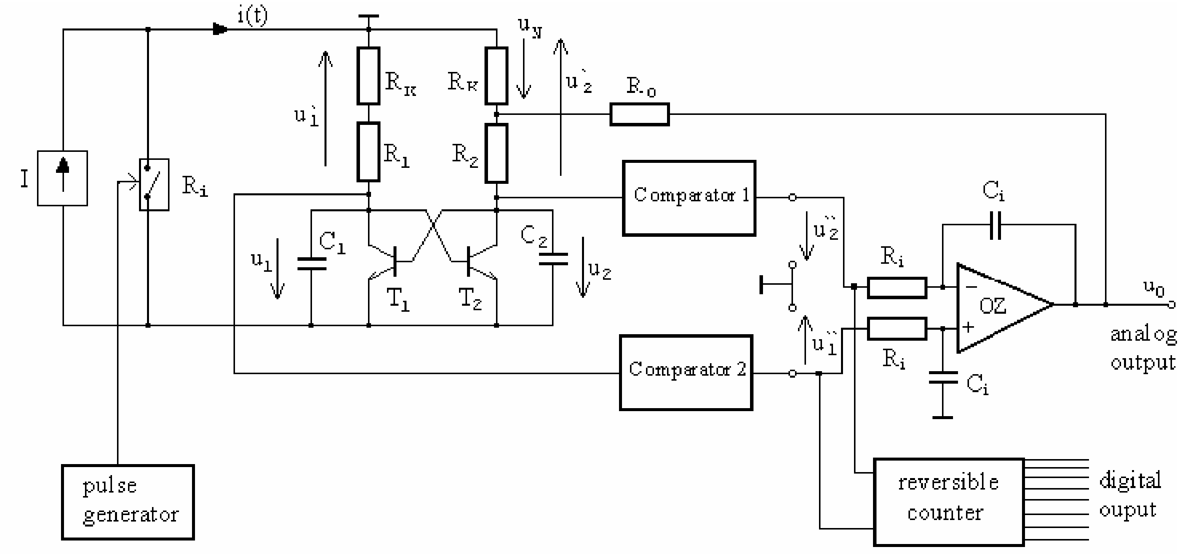

Fig. 3 Autocompensative system

4. Autocompensative system

The autocompensative system is shown in Fig. 3. R_1 and R_2 are the load resistors of the flip-flop and usually range from a few kΩ to tens of kΩs. R_k is small resistor its value is normally two orders of magnitude smaller than R_1 and R_2. Voltage u_0 is attenuated by the ratio R_0/R_k ($R_0 >> R_k$) and is fed to flip-flop sensor. By adjusting u_0, the asymmetry due to components in the flip-flop can be compensated, thus bringing the flip-flop sensor into 50% state [1]. The two outputs of the flip-flop are connected to comparators and the comparator outputs are connected to the integrator and reversible counter. The current of the flip-flop is switched on and off by a pulse generator. It is obvious that feedback is realized as analog, but reversible counter connected to the comparators enables to represent measured capacitance in the digital form.

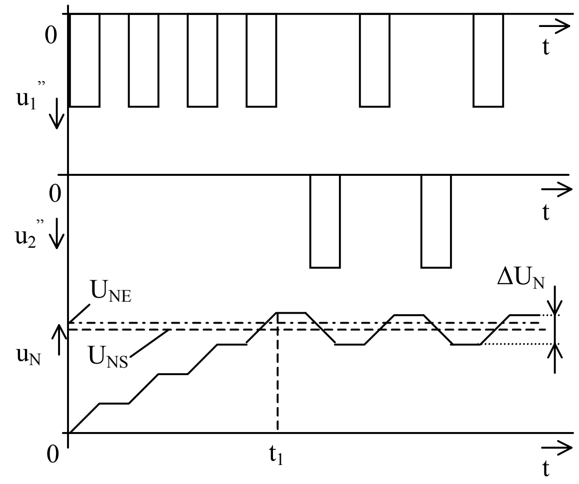

Fig. 4 Principle of autocompensative system functioning.

Now suppose that $C_1 > C_2$. From (7), it is obvious that $U_{NE} > 0$. After connection of the current generator voltage u_N increases, but if $u_N(t_1) > U_{NE}$, then beginning with this moment the situation starts to alternate which means the logical one will appear alternately at the output of the first inverter and then second inverter. This fact is expressed by Fig. 4. From the Fig. 4 it follows that the measured capacitance will be reflected into the mean value U_{NS} of the symmetrizing voltage u_N.

5. Experimental results

Results of theoretical considerations were proved by a lab experiment. Experimental circuit was made by SMT.

The important parameter of the flip-flop sensor is offset voltage. Let the offset voltage depends on temperature changes, mismatches in resistances and capacitances, mismatches in transistor saturation currents and current gains. Assume that the two transistors are subjected to the same temperature and that the effect of mismatches in the transistor saturation currents and current gains and of mismatches in the resistances of the flip-flop are negligible compared with the effect of mismatches in the capacitances of the flip-flop sensor. The major cause of offset voltage is then due to mismatches in the capacitances of the flip-flop sensor. The offset voltage can be compensated by the addition of a small DC voltage, or by the addition of a small capacitance, so that $C_1 = C_2$.

In case of our experiment $I_m = 1.17$ mA, R = 6.8 kΩ, $R_k = 10$ Ω, $R_0 = 1.8$ kΩ, $C_i = 10$ nF, $R_i = 10$ kΩ, $C = 387$pF so that offset voltage U_{NEOF} was equal to 8.3 mV. The offset voltage U_{NEOF} was measured indirectly proceeding 1:

- First, mean value of the voltage u_0 was measured (Fig. 3) using analog filter,
- Offset voltage U_{NEOF} was calculated using formula:

$$U_{NEOF} = -\frac{R_K \overline{U_0}}{\left(R_K + R_0\right)},$$

where $\overline{U}_0$ is mean value of the voltage u_0 and R_K, R_0 are resistors of the autocompensative system (see Fig. 3).

Using (7) for mismatches in the capacitances we have $\Delta C_1 = 0.806$ pF. Now suppose that measured capacitance ΔC_2 is in parallel connected to capacitance C_1. The capacitance ΔC_2 can be calculated using

$$\Delta C_2 = \frac{2U^{`}_{NE} C}{R I_m} - \Delta C_1 \tag{8}$$

where $U^{`}_{NE}$ is equivalent voltage with offset.

The formula (8) was derived through (7) under condition that $\Delta C = \Delta C_1 + \Delta C_2$.

This idea to measure the capacitances with compensation of the offset was used in the experiment. In Fig. 5 measured equivalent voltage with compensated effect of offset in the range from 0.5 pF to 3.5 pF is shown. The equivalent voltage U_{NE} was measured indirectly proceeding 2:

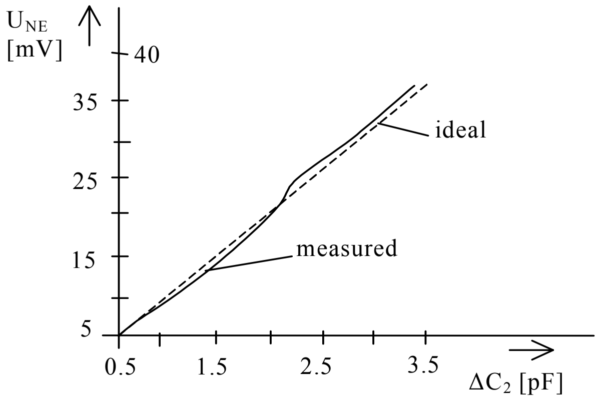

Fig. 5 Result dependence between the voltage U_{NE} and ΔC_2

- Mean value of u_0 measured (Fig. 3) by analog filter.
- Equivalent voltage $U^{`}_{NE}$ with offset computed using

$$U^{`}_{NE} = -R_K \overline{U_0} / \left(R_K + R_0\right),$$

where $\overline{U_0}$ is mean value of the voltage u_0 and R_K, R_0 are resistors of the autocompensative system (Fig. 3).

- Equivalent voltage U_{NE} without offset was calculated as $U_{NE} = U_{NE}' - U_{NEOF}$ where U_{NEOF} is offset measured by proceeding 1.

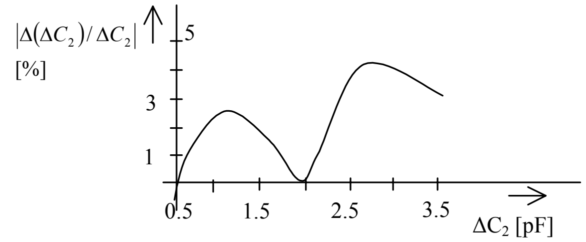

Fig. 6 The relative error as a function of the capacitance ΔC_2

In Fig. 6 absolute value of relative error is plotted versus measured capacitance.

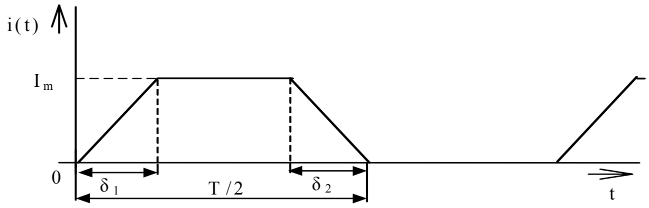

Fig. 7 Current control pulse

Where $\Delta(\Delta C_2) / \Delta C_2 = (\Delta C_2 - \Delta C_2') / \Delta C_2$ so that ΔC_2 is measured capacitance by using capacitive bridge and capacitance $\Delta C_2'$ was calculated by (8) under assumption that U_{NE}' is equivalent voltage with offset and ΔC_1 is initial difference of the capacitances of the flip-flop sensor. In the case of our experiment $\Delta C_1 = 0.806$ pF.

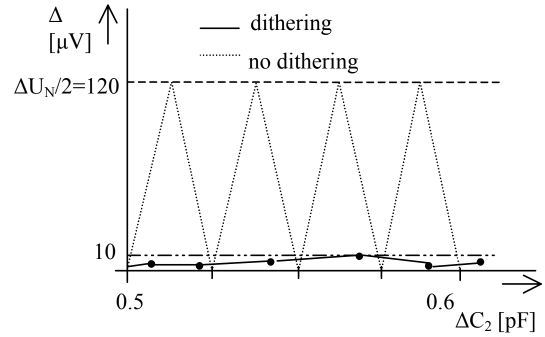

Fig. 8 Absolute error of the equivalent voltage Δ corresponding to parameter values by part 5.

The sensor was controlled by current pulse according to Fig. 7, while $\delta_1 = \delta_2 = 100$ ns, $I_m = 1.17$ mA, $T = 100$ μs.

As described above, value of the measured capacitance is reflected into the mean value of the symetrizing voltage u_N and then for absolute error we get $\Delta = |U_{NE} - U_{NS}|$. The absolute error as function of the capacitance has a shape of the periodical triangular wave, which amplitude is $\Delta U_N / 2$ (Fig. 4). But this error was neglected because a thermal noise of the parts of the flip-flop can be used for generating a dithering signal, so that then the result absolute error is smaller than 10 μV (Fig. 8). In Fig. 8 absolute error Δ with and without dithering in the range from 0.5 to 0.6 pF as result of simulation in MATLAB is shown.

In Fig. 9 the voltage u_0 as example of result of the laboratory experiment with effect of dithering can be seen.

It is obvious that in the case of our experiment the measuring range was to 3.5 pF. From (7), the measuring range can be changed by a value of the current I_m, resistor R and capacitance C respectively. The possibility to change the measuring range is not investigated in this paper.

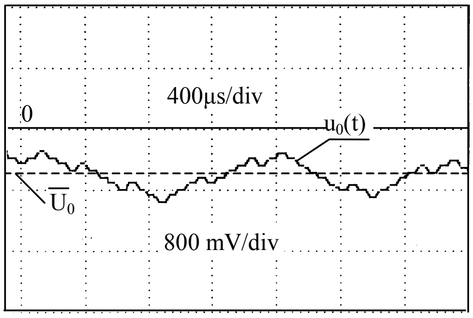

Fig. 9 The voltage u_0 as example of result of the laboratory experiment with effect of dithering.

6. Conclusions

In the paper, possibility of capacitances measurement with autocompensative flip-flop sensor is shown. Proposed method of capacitances measurement enables to compensate offset of the flip-flop sensor.

The validity of the formula for the calculation of equivalent voltage was proved by laboratory experiment. The agreement of real and measured value of the capacitance is good. From obtained experimental results it follows that the inaccuracy of measured capacitance is less than 4.5%.

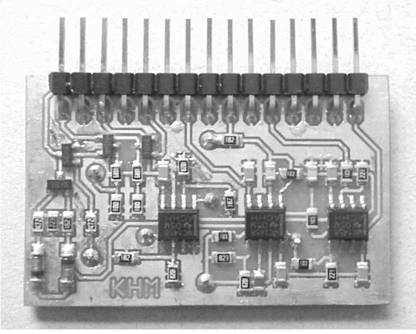

Fig. 10 A photography of the experimental circuit

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Martin KOLLÁR was born in 1974 in Spišská Nová Ves, Slovakia. This time he is Ph.D. student at the Department of Electronics and Multimedia Communications.

Viktor ŠPÁNY (Prof, Ing, DrSc), received his DrSc (DSc) degree from the Slovak University of Technology in Bratislava, Czechoslovakia. After joing the University of Technology in Kosice in 1952 his reserach was devoted to pulse circuits and digital electronics. The results of these activities, published in local and international journals, have been summarized in the book Bipolar Transistor in Pulse Circuits. He directed his further activities toward numerical and graphical solutions of non-linear dynamical systems. Among the most important results were the algorithms for construction and utilization of boundary surfaces in flip-flop circuits and oscillatory systems. Currently he is Professor Emeritus of electrical engineering at the Department of Electronics and Multimedia Telecommunications.

Tomáš GABAŠ (Ing.) was born in 1977 in Zvolen. He started his Ph.D. study at the department after defending his diploma thesis "Thick films gas sensors" in 2000. The topic of his next work is oriented to thick films sensors.

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